Laser Beaming Experiment

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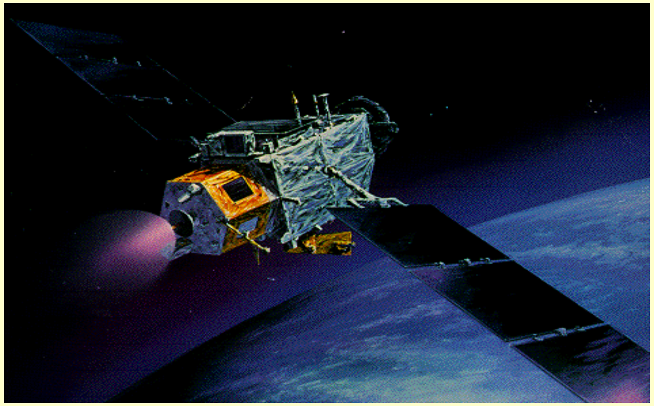
Presentation Overview

- Benefits of power beaming
- NPS research in this area
- Proposed experiment

Benefits of Power Beaming

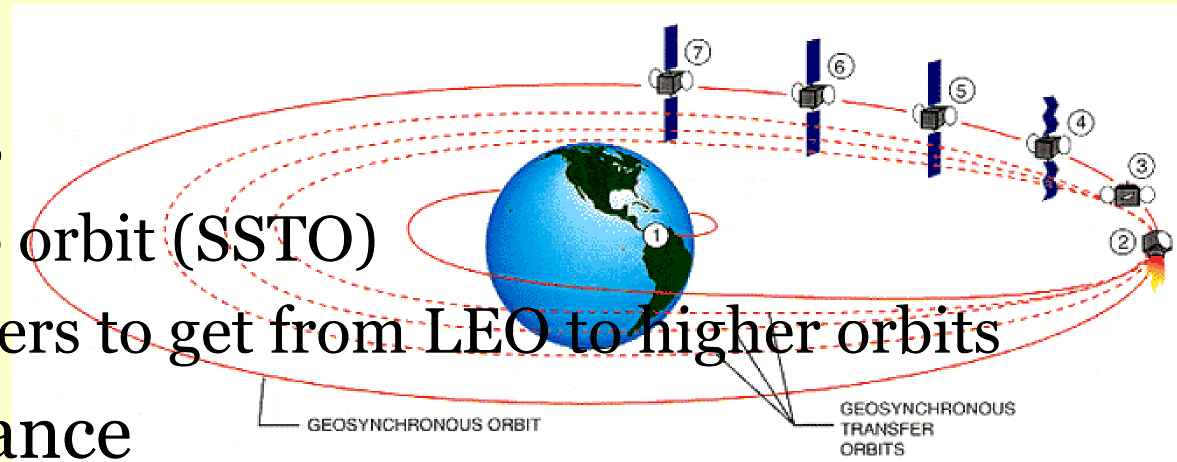
Mission Needs

- Power beaming for electric propulsion
  - Transfer orbits / LEO to GEO orbit raising
  - Orbit maintenance / station keeping
  - Orbital maneuvering



- Solar panel annealing
  - Repair radiation damage
  - Prolong mission life
- Complementing spacecraft power generation
  - Providing power during eclipse

Power Beaming for Electric Propulsion



- Transfer orbits
  - Single stage to orbit (SSTO)
  - Use ion thrusters to get from LEO to higher orbits
- Orbit maintenance
  - Correct for orbital perturbations
  - Eliminate or reduce need for hydrazine thrusters
- Orbital maneuvering
  - On-orbit servicing, refueling, inspection

Repositioning and Station Keeping

- Sometimes need to change subsatellite point
  - Changing mission requirements
  - Space control: evasive maneuvers
  - Electric propulsion ideal
  - Laser power can cut maneuver times in half
- Also need small amounts of thrust to correct for orbit perturbations
  - Electric propulsion ideal
  - Laser power can enhance solar flux

Propulsion Options

- Chemical rocket engines are powerful but heavy and have relatively low I_{SP} (~300 sec)
- Electric thrusters produce low thrust but have much higher I_{SP} (~1,000 to 5,000 sec)
  - Plasma thrusters, ion engines, etc.
- Thermal thrusters produce moderate thrust and have moderate I_{SP} (~600 sec)
  - Large mirror concentrates laser energy to directly heat hydrogen fuel

Solar Panel Annealing

- Radiation damage
  - Trapped energetic particles break down crystal structure of semiconductor materials
  - Degrades solar cell performance
  - Worse in some orbits than others
- Annealing can repair this damage
- Prolongs mission life
  - Many satellites reach end of life due to insufficient power

Complementing Spacecraft Power Generation

- Can reduce or eliminate need for batteries
- Some space applications require high power for a short amount of time
- Lasers can beam power during eclipse or can complement solar flux on panels
- Requires spacecraft to be designed to handle increased power generated

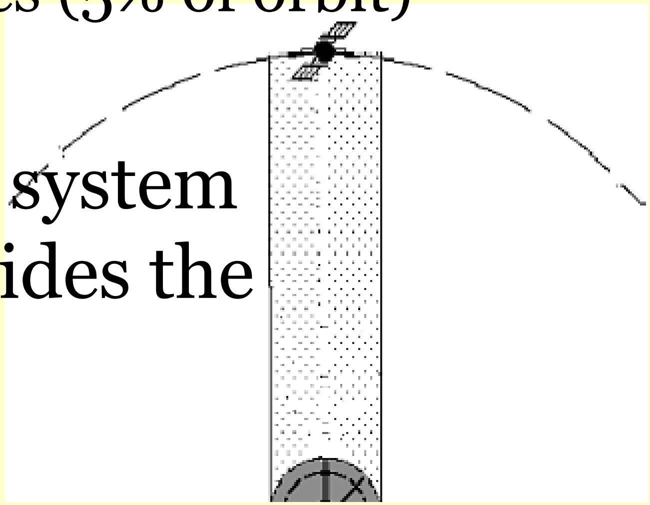
NPS Research in This Area

Economics of Orbit Raising

- An average GEO satellite weighs 3500 lbs
- Chemical rocket and fuel typically weigh four to five times the amount of the payload
- Launching Earth to LEO costs $5K per lb
- Cost to transfer from LEO to GEO is $100M
- 17 comm & 6 mil GEO launches per year
- This easily adds up to over $1B per year!
- Is this cost effective over the long run? Could the cost of power beaming sites be shared internationally?

GEO Power Generation

- GEO satellites make up a large proportion of commercial spacecraft
- GEO satellites are in eclipse during two periods of 45 days centered on the equinoxes
  - Total = 90 days per year
  - Max eclipse duration = 69 minutes (5% of orbit)
  - Less than 1% of the total lifetime
- During eclipse period a battery system charged by the solar array provides the primary power



GEO Power Generation

- As the satellite enters eclipse, the laser illuminates the satellite solar panels to a level sufficient to provide operating power
- Each ground laser station can successively illuminate several satellites at different longitudes
  - As one satellite exits the eclipse region, the laser is retargeted to another satellite entering eclipse
  - Even if a ground-based laser can scan only an angle of ±45° from zenith, a single laser station could provide power for five satellites at different longitudes

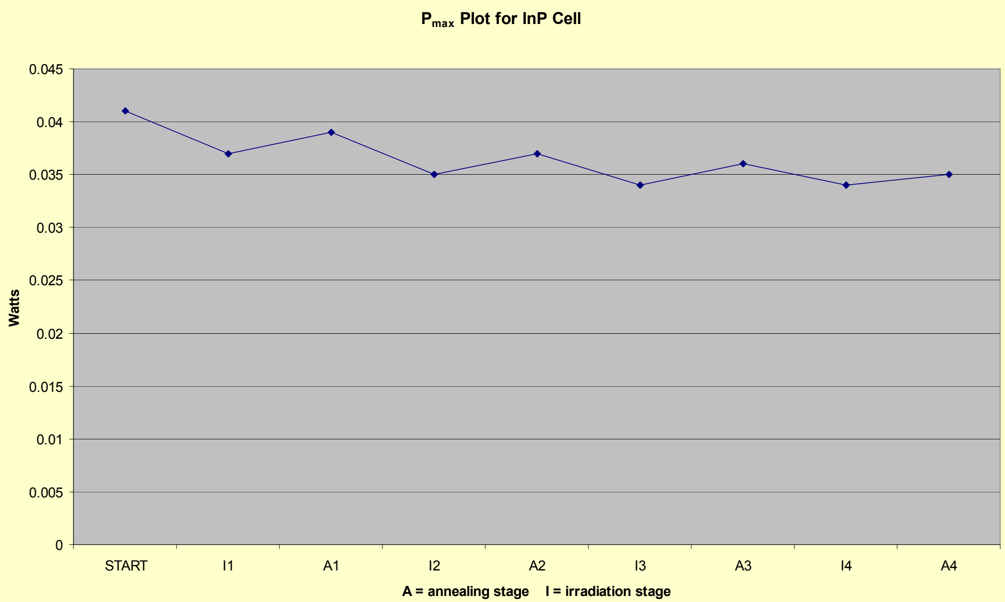
Economic Study Results

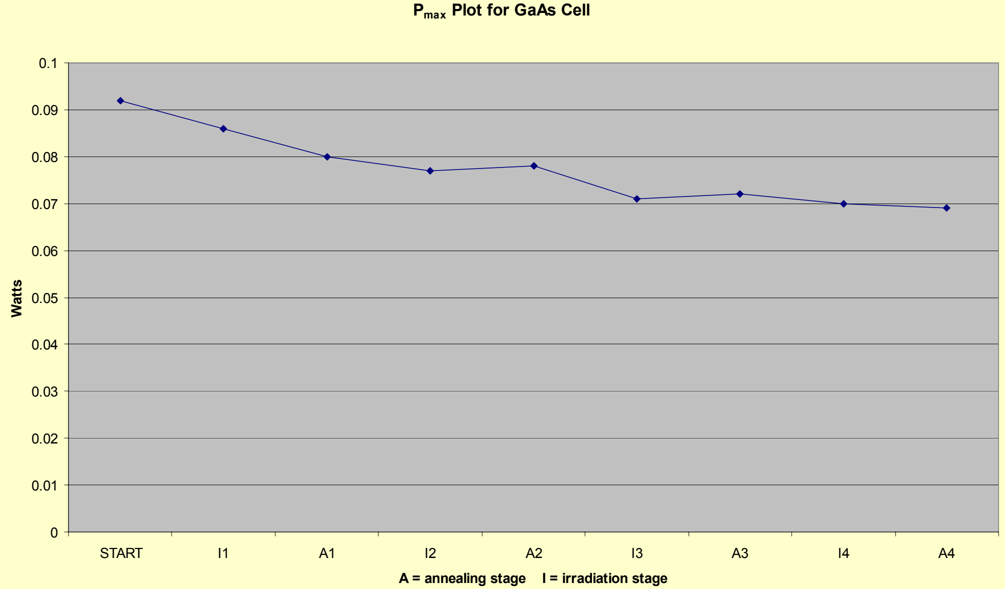
- Commercial satellite industry can reap significant economic benefits through use of power beaming
- Now battery lifetime is the limiting factor, but power beaming can provide supplemental power for satellites with failing arrays, or primary power in the case of failed batteries
- Today there are 22+ satellites operating past design life, generating total revenues ~ $500M
- Future satellites could be designed without large batteries, allowing a 20-30% increase in payload for considerable additional savings

Solar Panel Annealing

- Nine theses completed on repairing radiation-damaged solar cells
- Forward biasing of InP and GaAs cells shows most damage can be repaired
  - The less damage that occurs, the better the recovery
  - Lasers shown to generate enough current to anneal cells at realistic temperatures
- Future interest in multi-junction annealing

Annealing Results





Proposed Experiment

Research Approach

- Literature review and personal interviews
  - Survey of relevant research and theses
  - History of high-energy laser use
  - Satellite solar cell characteristics
- Theoretical predictions
  - Response of solar cells to various λ light
  - How much power at what λ can get to LEO

Research Approach

- Experimentation
  - Ground, using simulated aged solar cell materials
  - Space, using suitable target satellites
- Comparison
  - Demonstrate that response of solar cells on orbit matches that predicted by theory and in the lab
  - Extrapolate results for future systems that could be optimized for HEL benefits

Candidate Ground Facilities

- Air Force Research Lab Starfire Optical Range

Candidate Ground Facilities

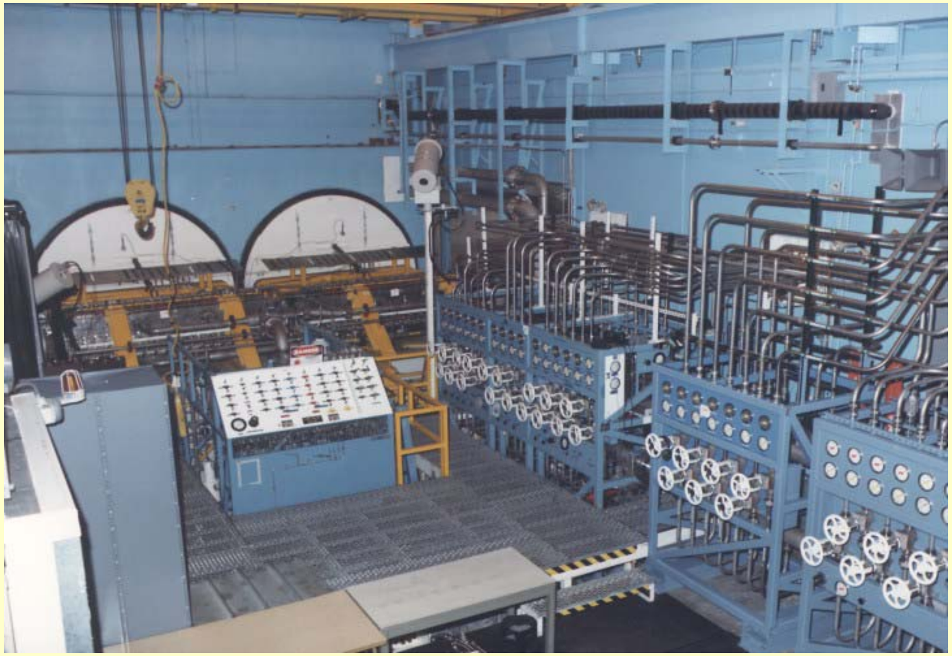
- Maui Sites
  - Air Force Maui Optical and Supercomputing Station (AMOS)
  - NASA/University of Hawaii LURE facility

Candidate Ground Facilities

- MIT Lincoln Labs Firepond Optical Facility
  - Nd:YAG Lidar tested at 24W output at 30 Hz

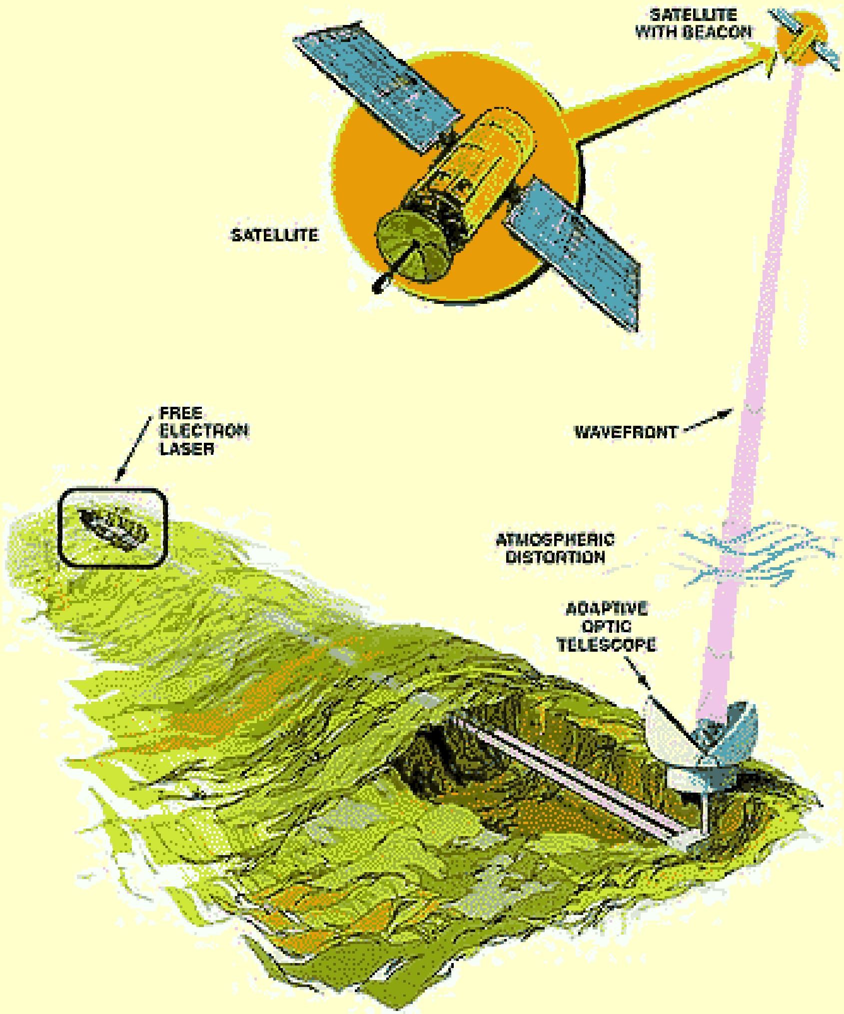
Candidate Ground Facilities

- Army White Sands Missile Range MIRACL Site
  - Megawatt-class DF laser (3.6-4.2 μm)



Candidate Ground Facilities

- Navy China Lake SELENE Project
  - Now run by Bennett Optical Research
  - Designed to use FEL and adaptive optics to beam power



Summary of Ground Facilities

Site Name	*Location*	*Avg Power*	*λ*	*eV*
SOR*	Kirtland AFB, NM	400 W 150 W	1.06 μm .532 μm	1.17 2.34
AMOS*	Maui, HI	30 W	.532 μm	2.34
Firepond	Bedford, MA	24 W	.532 μm	2.34
MIRACL	White Sands, NM	2.2 MW	3.8 μm	0.33
SELENE	China Lake, CA	200 kW	400 μm	3.1

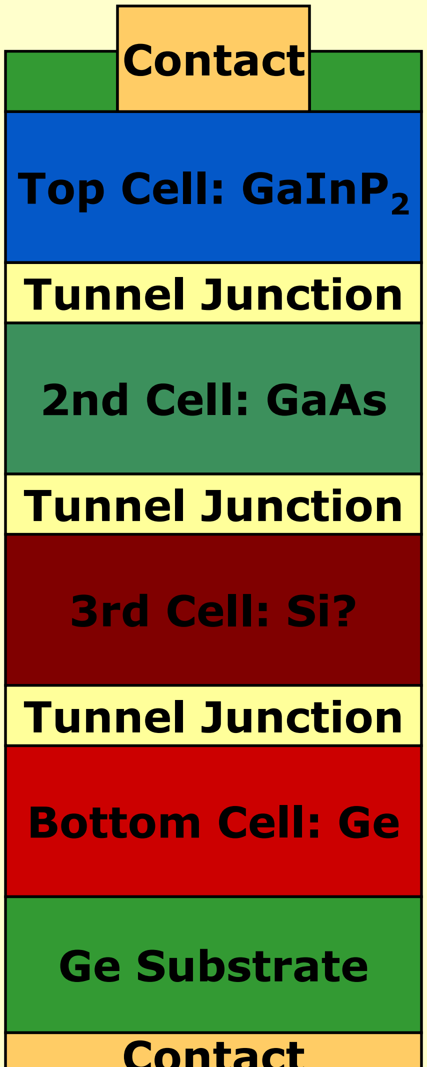
* *indicates most likely sites*

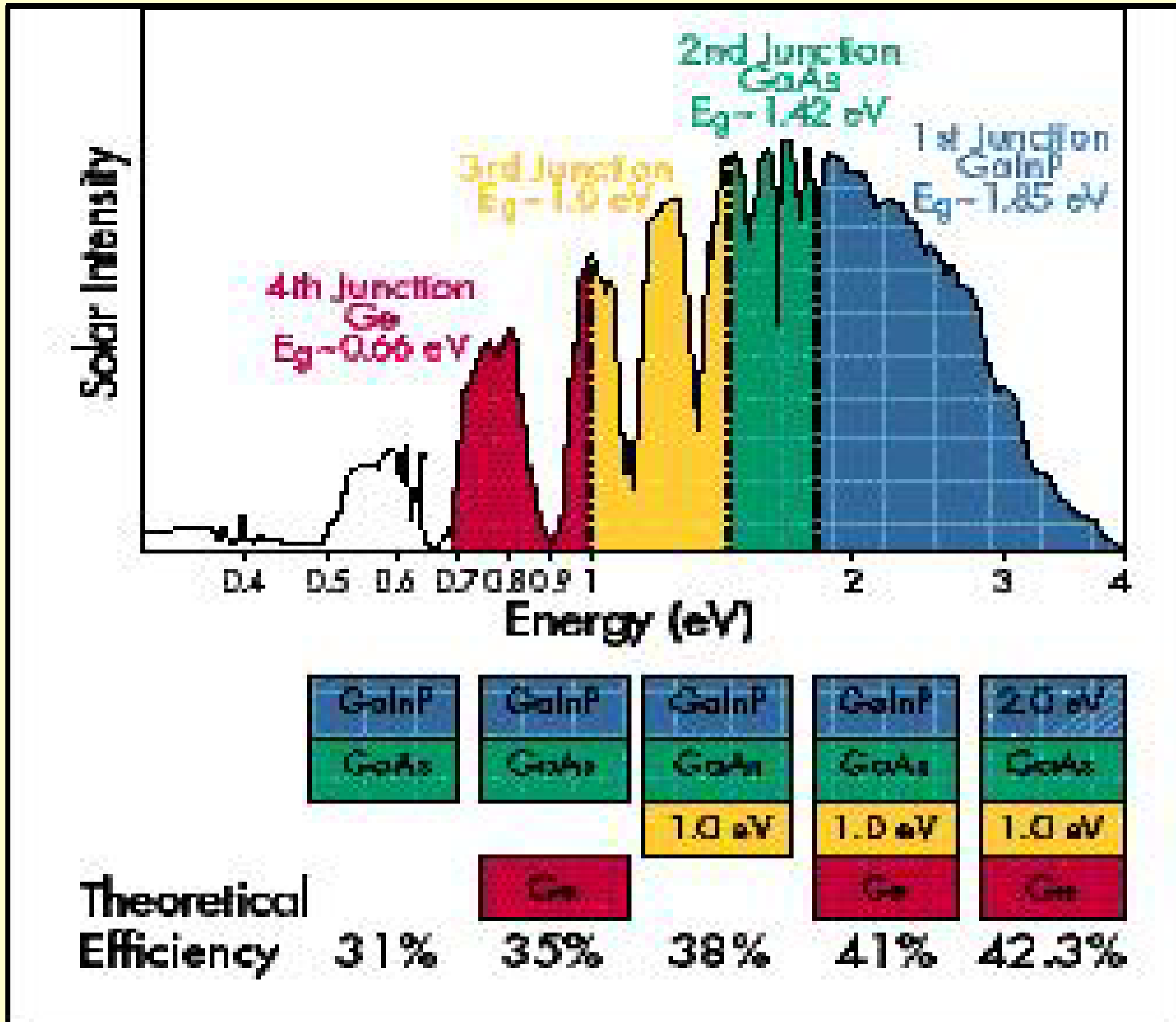
Laser/Solar Cell Matching

Lasing Medium	Wavelength	eV	Atmospheric Transmission
Frequency Doubled Nd:YAG	532 nm	2.34	70%
Diode	850 nm	1.46	80%
Nd:YAG	1.06 µm	1.17	92%
DF	3.8 µm	0.33	95%
CO_2	10.6 µm	0.12	95%

Solar Cell Material	Minimum Required eV
Ge	0.66
Si	1.10
GaAs	1.42
$GaInP_2$	1.85

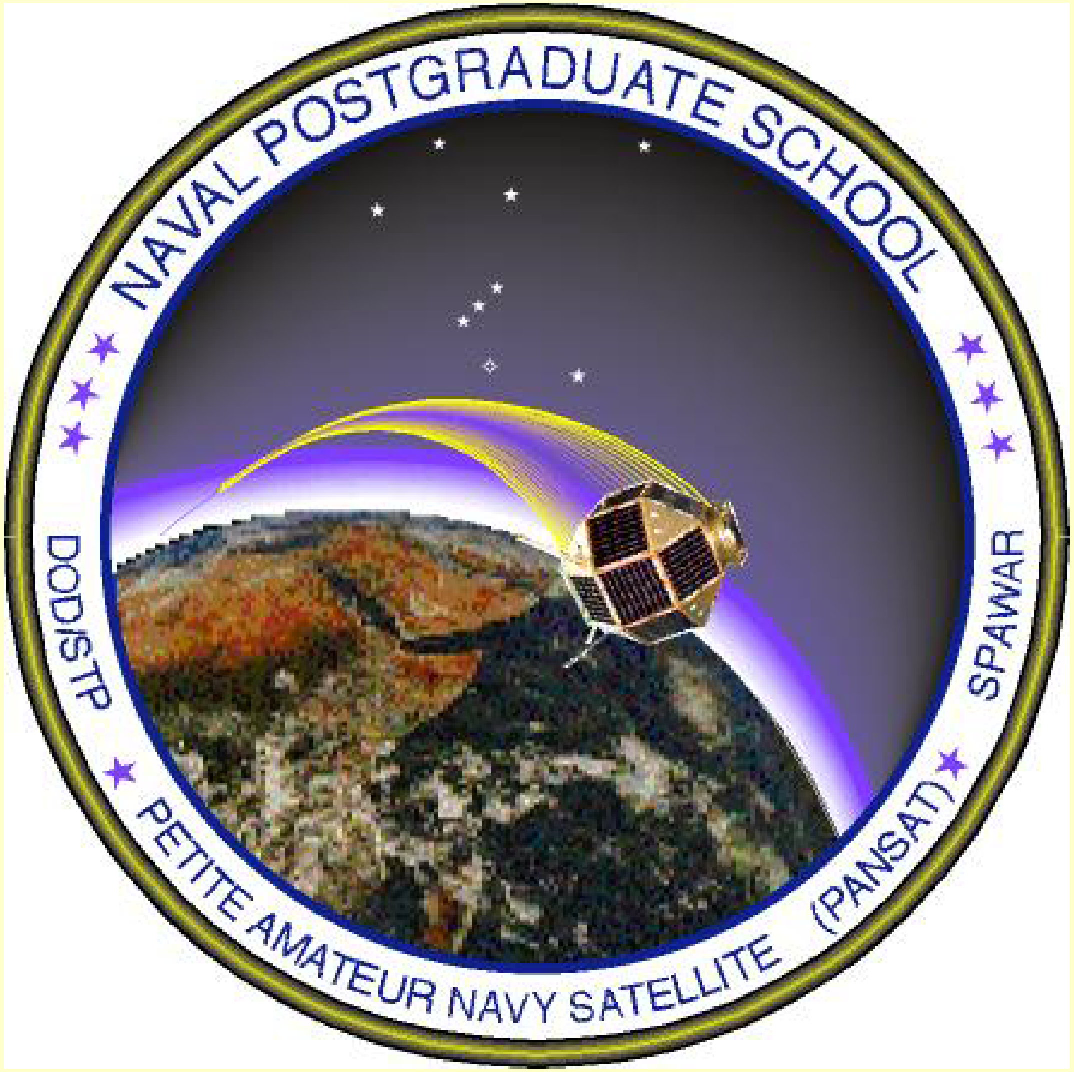
Multi-Junction Solar Cell





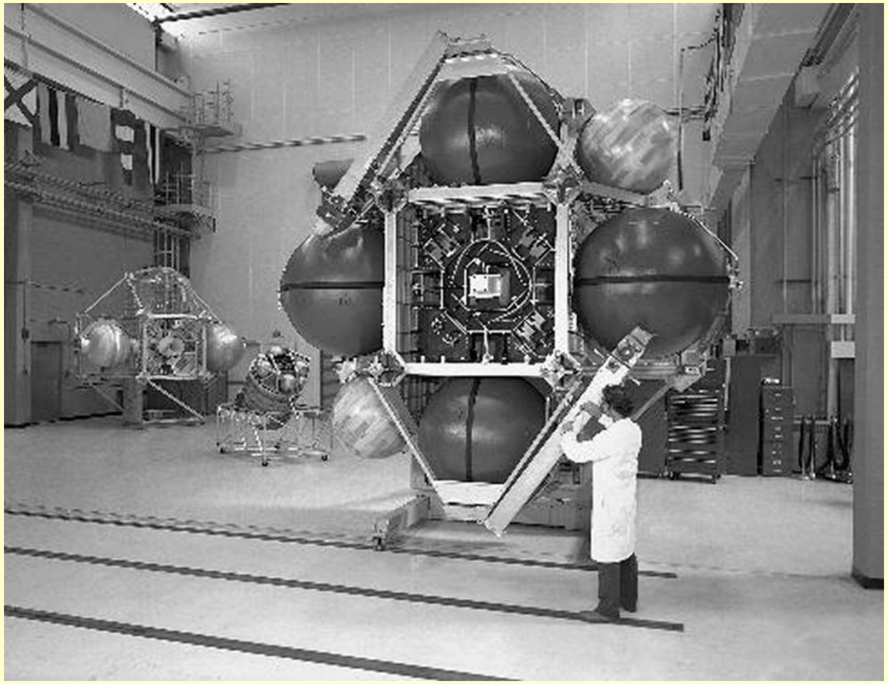
Candidate Target Satellites

- Navy Postgraduate School PANSAT
  - Altitude: 300 nm (555 km)
  - Inclination: 28.5°
  - 16 panels Si solar cells; 1 panel GaAs solar cell
  - Has been on orbit almost four years (launched Nov 98)
  - Telemetry comes into NPS
  - Most likely choice



Candidate Target Satellites

- Navy Research Lab TLD (Titan Launch Dispenser)
  - Si solar cells
  - Has been on orbit for over six years
  - Backup choice



Conclusion

Conclusion

- Looking for interested customers and research partners (AFRL/DE on board)
- Seeking funding to purchase materials, conduct tests, and cover travel
  - Test prep, materials, site costs $ 75K
  - Travel and equipment $ 50K
  - Total funding needed $ 125K

- No overstatement to say that successful demonstrations could revolutionize spacecraft design and mission planning

Other Supporting Studies and Research

Electric Power

- Average GEO satellite costs about $250M and earns $25M-$50M per year
- They are in eclipse for 90 days a year for up to 70 minutes at a time
- Rechargeable batteries are used to power the spacecraft during eclipse, but they are the most common failure item

Interesting Facts

- 20% of the mass of a typical GEO comm satellite is the power system
- Eclipse is less than 1% of the operating time
- Over half of the mass of the power system has no other function than to provide power during eclipse
- Eliminating the need for energy storage would reduce satellite mass by 10%

The Bottom Line

- Power beaming from the ground will save satellite mass, complexity, and cost
  - Lower launch costs
  - Higher satellite reliability
  - Longer satellite lifetimes
- Must be traded off against cost of building the ground-based facilities

Key Steps

1. Locate the satellite
2. Center it in the beam-projection telescope
3. Follow it as it moves
4. Project a properly aligned laser beam
5. Overcome atmospheric turbulence

Demonstrations began in 1965!

AFRL Orbit Transfer Study

- Use 370 kW CW lasers to deliver 110 kW
- 4 sites worldwide with 4 m beam directors
- LEO to GEO transit would take ~ 40 days
  - Typical chemical thruster transfer is 1-3 days
  - Concerns with long dwell in Van Allen belts

NASA Analysis

- Peak efficiency for Si cells is at 950 nm
- Peak efficiency for GaAs cells is at 850 nm
- Response of solar cells to monochromatic illumination near optimum wavelength is roughly double that produced by sunlight
- This means that to get ~ 1 sun of illumination requires 915 kW/m^2 at 850 nm

Navy Power Beaming Study

- Cost per kg of useful payload is reduced by more than 1/3 using laser power beaming instead of rockets for LEO to GEO transfer
- Estimated cost of setting up laser power beaming infrastructure at over $1B
- Projected this money would be made back in less than a year!

Proposed Solutions

- Quadrupling electrical power from solar panels requires 3 kW/m^2 of laser flux
- One solution proposed by Sandia uses a 200 kW laser with an 8 m beam director
- NASA proposes linking many smaller lasers together (total ~200 kW) with smaller optics

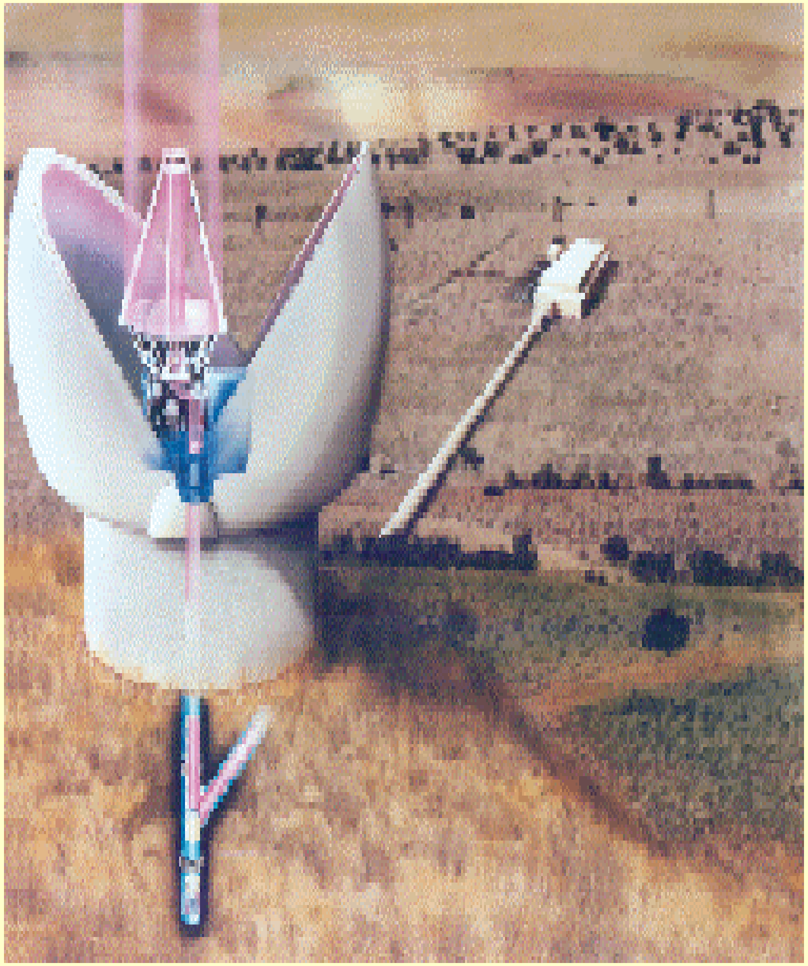
The SELENE Corporation

- Headquarters in Lompoc, CA
- Started out as a Navy project at China Lake
- Laser-powered “Space Tug”
- Estimated $350M construction/launch cost
  - $25M power beaming complex, 12 m AO telescope
  - Russian-designed 200 kW FEL built by Berkeley Lab
  - Space Tug satellite
- Current status--spent about $10M and…

Conclusion

- Introduction
- Motivation for Power Beaming
- History and Previous Experiments
- Current Status and Future Plans
- Conclusion

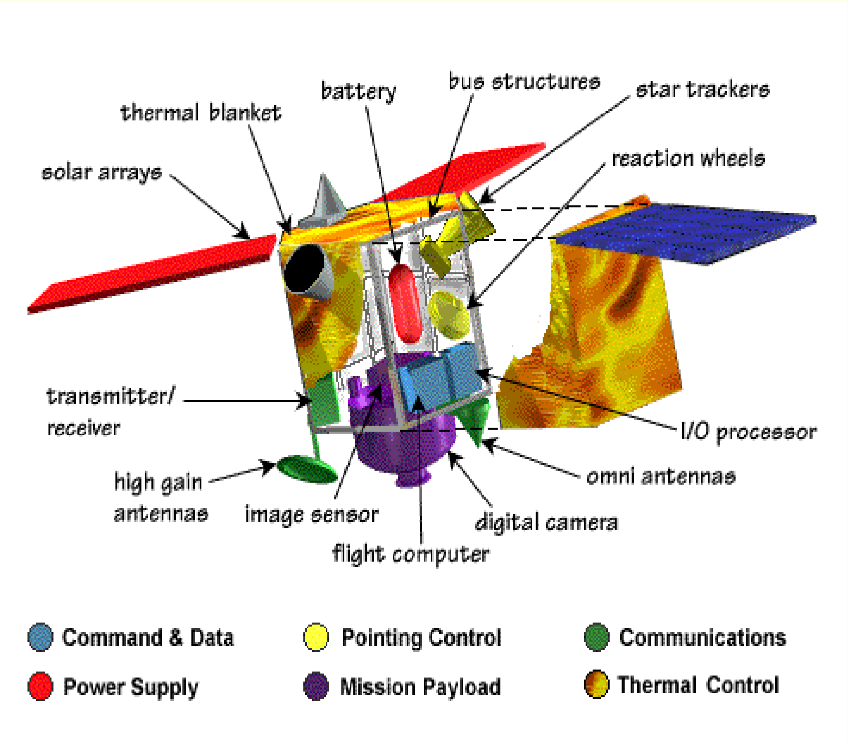
A LASER BEAMED POWER SATELLITE



- It is possible to use a ground-based laser to beam light to the solar arrays of orbiting satellite, to a level sufficient to provide all or some operating power required.
- Power beaming might be to provide power to existing satellites at or near the end of life (EOL) due to power system degradation.

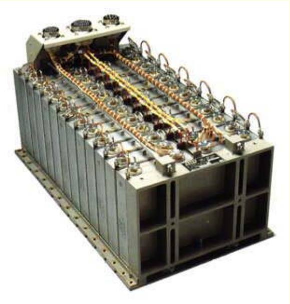
End of life Condition (EOL)

- Failure of the power system.
- The other systems are proving to be unexpectedly robust, with minimal problems once the satellites have reached operational status. So, two types of power failure or degradation occur:
- 1. Battery Failure due to random internal shorts or capacity degradation.
- 2. Solar Array Degradation due to accumulated radiation exposure.



AFRL's Lightweight Flexible Solar Array

- Solar array degradation, reduce the amount of power, but does not, in general, cause complete failure of satellite.



- Battery failure, is typically an abrupt failure, and results in end of life for the satellite.

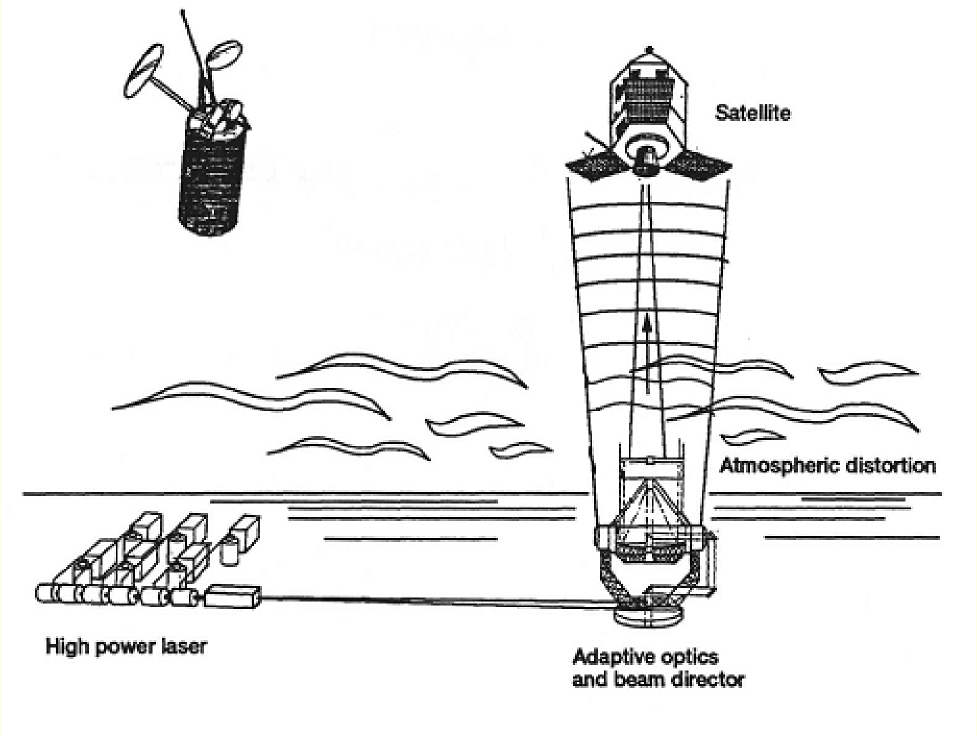
Typical Power Requirements
COMSTAR satellite
(24 C-Band transponder, 28 V power bus)

Housekeeping	2.2 A 61.6 W
Transponders Total	0.7 A 19.6 W (each) 470.4 W
Required Power Subtotal	470.4 W
Battery Charging	1.5 A 42.0 W
TOTAL	**544 W**

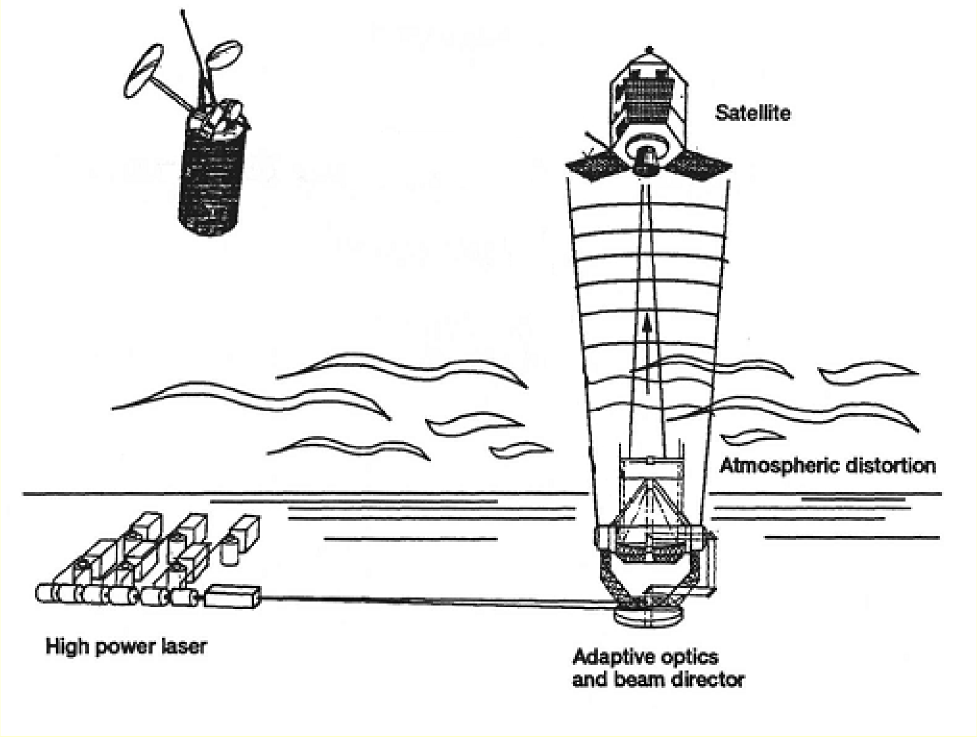
- 20 to 25 new commercial satellites are launched each year.
- Investment are of about $136 million for medium sized communications satellite, and near $250 million for a large satellite.
- There are satellites which have exceeded design end of life and are continuing in operation. Each of these is currently dependant on the successful operation of their batteries, which will fail in the next few years.
- All of these are candidates for lifetime extension by Laser Power Beaming.

- There are above 22 satellites which have exceeded design end of life and are continuing in operation.
- The typical size of these satellites is approaching 24 transponders.
- The revenue generated from a transponder can be \$2M/year.
- For revenue generated by old satellites, we assume a 50% discount, and thus each transponder can generate \$1M/year in revenue.
- The operating costs of these satellites are less than \$1M/satellite per year.
- Therefore, since these older satellites are already fully depreciated, the economic benefits of laser power beaming to replace failed batteries are enormous, potentially as high as \$500 M/year today.

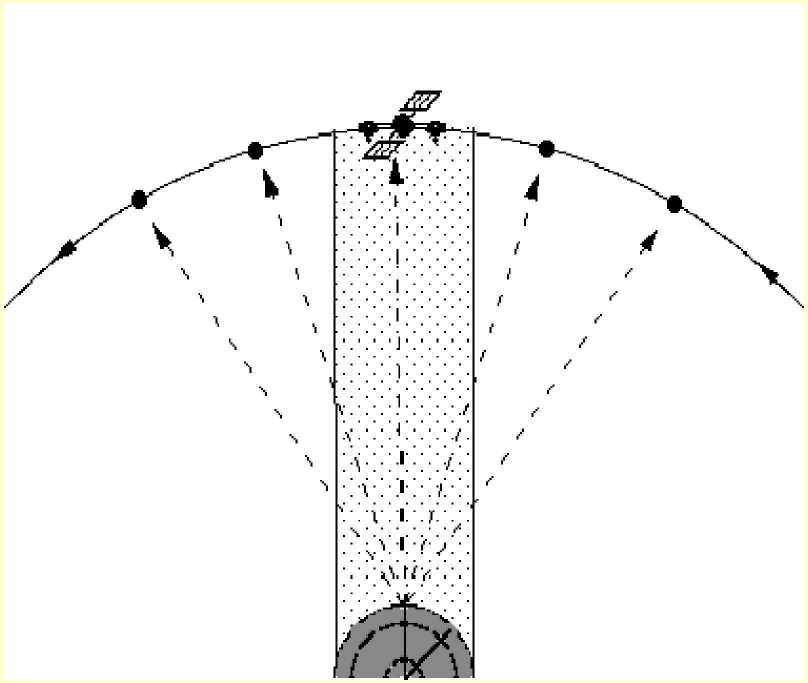
GENERAL SYSTEM CONSIDERATIONS
Systems Components



- A high power laser capable of putting out a high average power for a long duration.
- An adaptive optics system to compensate for distortion of the laser beam as it traverses the Earth's atmosphere.
- A large optical element to minimize the diffraction of the beam, including a pointing and beam control system.
- A photovoltaic receiver on the satellite.

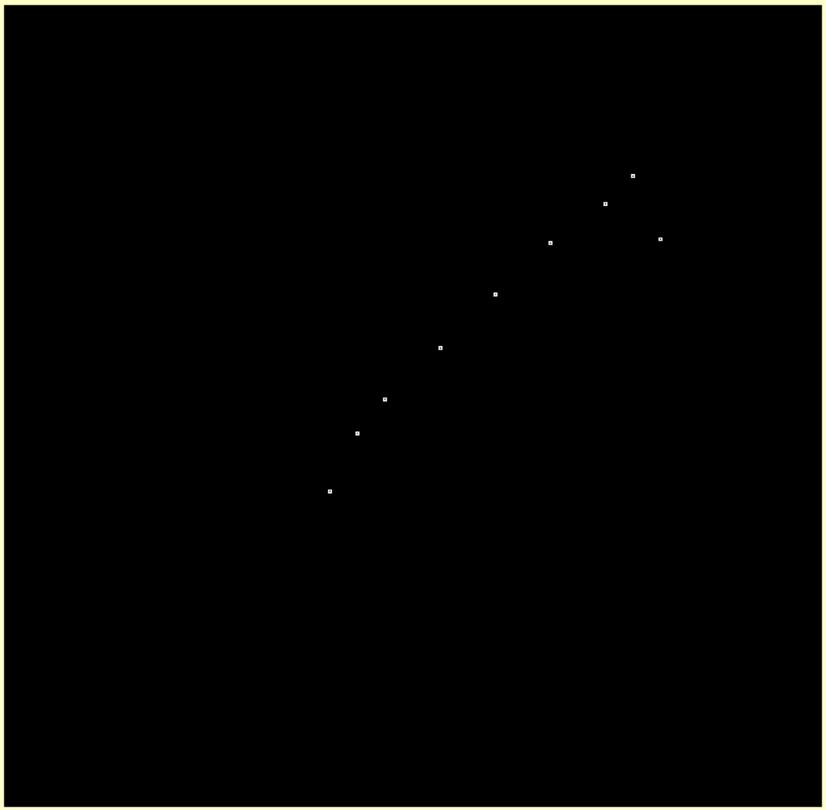


- The laser wavelength must be chosen to be compatible with the spectral response of radiation-damaged solar cells, with a peak response near 800 nm, and moderate performance from about 600 to 900 nm.
- The solar array needed to receive the beamed power is already in place on the satellite.
- For the battery replacement mission, laser power is required only for periods of less than 70 minutes per day for 90 days out of the year. This allows ample time for laser refurbishment and



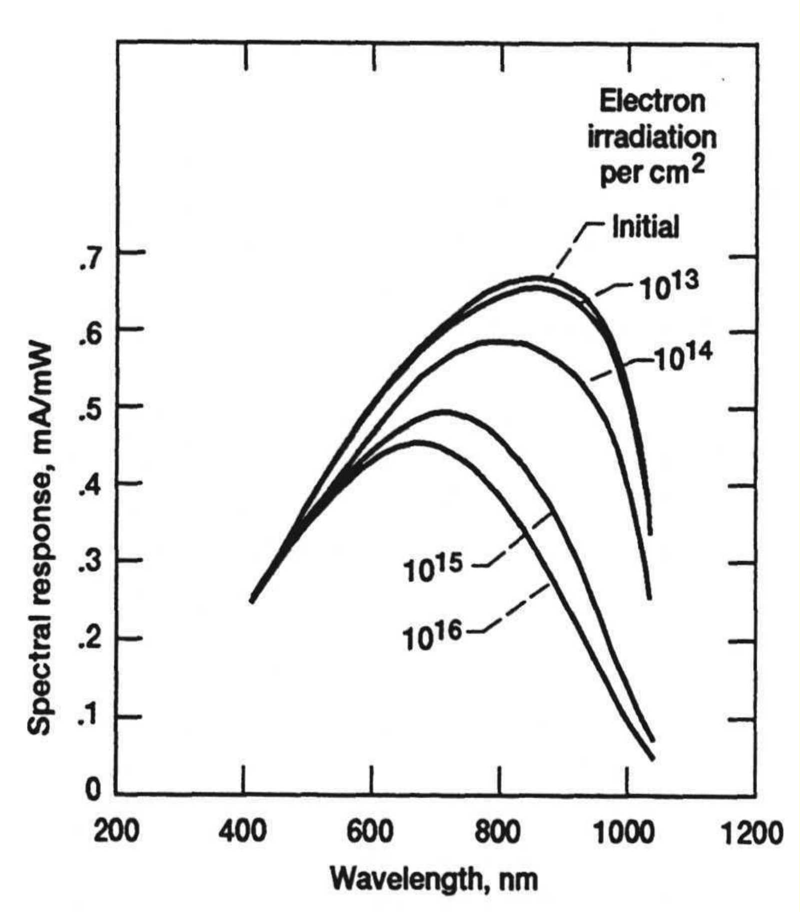
- As the satellite enters eclipse, the laser arrays illuminate the solar panels on the satellite to a level sufficient to provide operating power.
- The maximum angle from zenith for which the system can be used will be in the range of 45 to 60°.
- Each ground laser station can successively illuminate several satellites at different longitudes. As one satellite exits the eclipse region, the laser is retargeted to another satellite entering the eclipse. Even if a ground-based laser can scan only an angle of ±45° from the zenith, a single laser station could provide power for five satellites at different longitudes

Solar Cells
Photovoltaic Receivers on the Satellite



- Geo Satellites are subject to degradation in power due to trapped radiation and solar flares.
- The efficiency degrades to under 10% after long exposure to the space radiation environment.
- The efficiency increases under laser illumination, since the laser wavelength can be chosen to be near the optimum conversion wavelength.

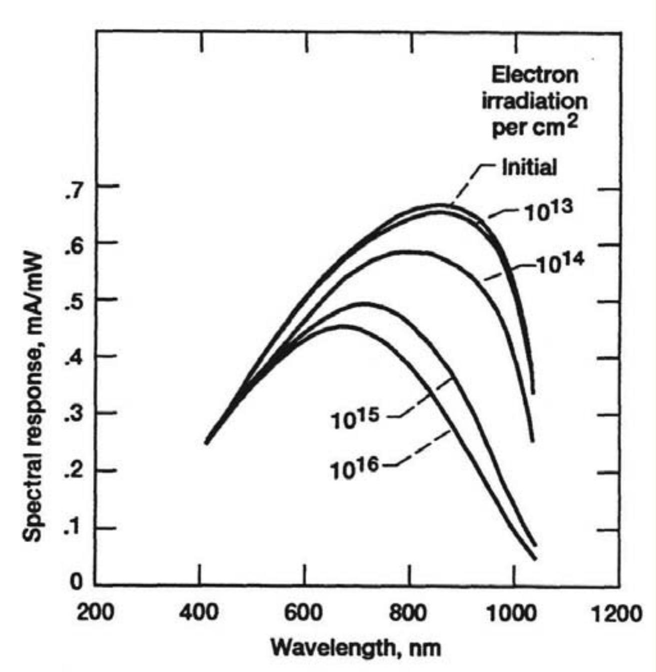
Spectral response of a conventional silicon solar cell



- Without radiation damage, the response is quite linear out to about 950 nm, but drops off rapidly above this value.
- With radiation damage, the wavelength of peak response decreases to around 700-800 nm.

The efficiency under laser illumination

$$\eta_{laser} = \eta_{solar} P_{sun} SR(\lambda)/J_{sc}$$



- η_{laser}, can be calculated if the spectral responds $SR(\lambda)$ and the short circuit and efficiency under solar illumination are known.
- P_{sun} equals 1370 W/m² .
- η_{solar}, is about 11% at BOL and 8% at EOL.
- J_{sc}, is about 0.034 A/cm² at BOL and 0.029 A/cm² at EOL.
- The peak of spectral response after 10^{15} e^-/cm² irradiation is about 0.5 A/W.
- The expected efficiency at end of life under laser illumination is 2.4 times the solar efficiency, or about 19%, for wavelengths near the optimum (roughly 750 nm).

Ground System

$$r_{spot} = 0.61 d\lambda / r_{lens}$$

- r_{lens} is the radius of the lens (typically a mirror) used to focus the beam.
- d the source to receiver distance.
- λ the wavelength.

- Using d=36,000 km (GEO), λ= 800 nm ($8 \cdot 10^{-7}$m) and r_{lens}= 2.5 m (large), the spot radius is 7 meters. The illuminated area is 150 m^2
- Increasing the mirror radius to 5 meters decreases the illuminated area to 38 m^2 at a considerable increase in mirror cost. For example, the cost of

ADAPTIVE OPTICS

- The effectiveness of the adaptive optic system is characterized by a Strehl ratio, which is the ratio of the actual peak intensity produced by the laser to the ratio which would be produced with no atmospheric distortion.
- For perfect compensation, the Strehl ratio would be unity. For systems of the type likely to be constructed in the near future, a Strehl ratio of 0.85 could be expected for a vertical beam, decreasing to 0.65 at 60° zenith angle.
- For the 2.5-meter radius mirror, producing 570 W/m^2 would require a laser power output of 120 kW at a Strehl ratio of 0.85. Increasing the mirror radius to 5 meters (38 m^2 illuminated area) decreases the laser power required to 31 kW. (This is a power level which is achievable with current technology).

LASERS

- Lasers to be considered must operate in the wavelength range centered around the visible spectrum and near-infrared in which the atmosphere is nearly transparent. If specific molecular absorption peaks are avoided, the atmosphere has high transparency in the 500-850 nm wavelength range where the solar cell conversion efficiency is

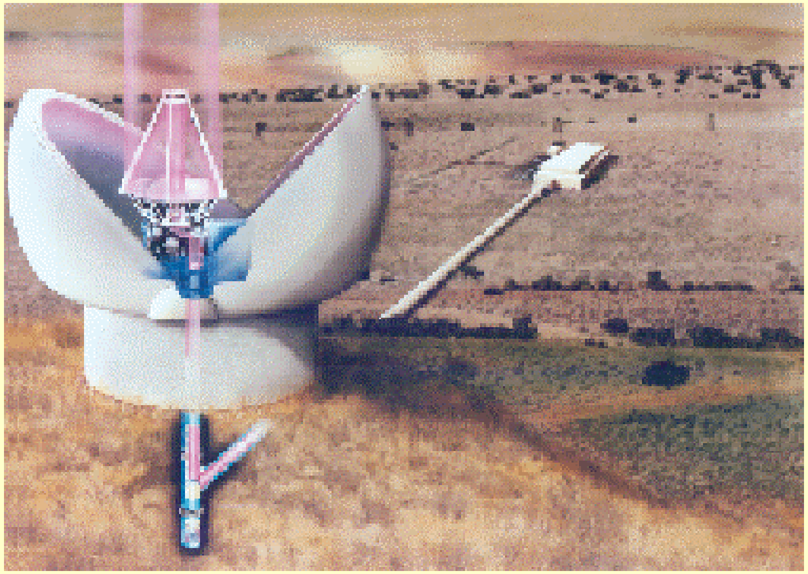
- Three laser types are well enough developed for consideration for near-term demonstrations of laser power beaming:
- The Neodynium: YAG laser.
- The Copper Vapor laser or CV-pumped dye laser.
- The RF Free Electron laser.

- Free Electron Lasers: the free-electron laser (FEL) is a very attractive choice. A FEL has potentially very high efficiency as well as high power and is, in principle, tunable over a wide range of wavelengths, 0.1 nm to 1 cm. Free electron lasers have been proposed in the multi-megawatt power range (high average power).
- FEL can be based either on induction or RF linear accelerators. The induction laser is potentially capable of high power, but is less well developed, and has not yet been operated in the wavelengths required. It may be a candidate for future, high-power missions. RF lasers are currently studied and operated at power levels of interest.

- YAG Lasers: Of currently developed laser technologies, the highest power CW lasers in the wavelength range of interest are Neodymium doped Yttrium-Aluminum Garnet (Nd:YAG). The wavelength of 1064 nm is theoretically possible to convert by silicon cells, but in practice, the production-technology silicon solar cells used on satellites currently flying have very low performance at 1064 nm. Further, the long wavelength response degrades rapidly in a radiation environment, and thus very little response at 1064 nm would be expected at satellite end of life. Frequency doubling the YAG to 530 nm results in a considerably better performance; however, frequency doubling will reduce both the laser efficiency and the laser power.

- Copper Vapor Lasers: Copper vapor lasers are inherently pulsed lasers, but have been demonstrated to produce average powers at levels of interest. The highest average-power continuously-run laser facility in the world is the AVLIS (Atomic Vapor Laser Isotope Separation) system running at Lawrence Livermore National Laboratories. The copper vapor lasers produce roughly 10 kW of average power at the two copper lines, 511 and 578 nm.
- This laser is used to pump a dye laser, at about 35% efficiency. In principle, operation at any wavelength of choice could be obtained by choice of an appropriate dye to be pumped by the copper laser.

CONCLUSIONS



- Illumination of a satellite in geosynchronous Earth orbit at levels sufficient to provide full spacecraft power should be feasible with arrays of lasers.
- Power is extremely cheap on Earth compared to the cost of power in space.